

ENVIRONMENT AND NATURAL RESOURCES PROGRAM

Is China's Hydrogen Economy Coming?

A Game-Changing Opportunity

Nicola De Blasio

Fridolin Pflugmann



HARVARD Kennedy School

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REPORT

JULY 2020

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The Environment and Natural Resources Program's mandate is to conduct policy-relevant research at the regional, national, international, and global level, and through its outreach initiatives to make its products available to decision-makers, scholars, and interested citizens.

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Glossary

Terms

BEV	Battery electric vehicle
BRI	Belt and Road Initiative
CCUS	Carbon capture utilization and storage
EV	Electric vehicle
FCEV	Fuel cell electric vehicle
NEV	New energy vehicle
RES	Renewable energy sources

Units

EJ	Exajoule (10^{18} Joule)
Mt	Million tons
PWh	Petawatt hour (10^{15} Watt hours)

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Chengdu, Sichuan, China.

Unsplash user Li Lin

Executive Summary

To accelerate the global transition to a low-carbon economy, all energy systems and sectors must be actively decarbonized. While hydrogen has been a staple in the energy and chemical industries for decades, renewable hydrogen is drawing increased attention today as a versatile and sustainable energy carrier with the potential to play an important role in the carbon-free energy puzzle.

Our recent article, “The Geopolitics of Renewable Hydrogen in Low-Carbon Energy Markets” explores the global implications of renewable hydrogen adoption at scale and shows that the role countries will likely assume in global renewable hydrogen markets depends on their renewable energy resource and freshwater endowments as well as their ability to deploy enabling infrastructure.

Using the same analytical framework, this paper focuses on China and the potential role of renewable hydrogen in accelerating its transition to a low-carbon economy. Our research goal is to provide policymakers and other stakeholders the means to make informed decisions on technology innovation, policy instruments, and long-term investments in enabling infrastructure.

Renewable hydrogen offers significant advantages for China. It can help Beijing meet its climate and pollution goals — at a time when coal continues to dominate — while avoiding increased reliance on imported fuels. As a readily dispatchable means of storing energy, hydrogen can also help to address intermittency and curtailment issues as renewable energy increases its share of China’s energy mix. Furthermore, hydrogen can open new avenues for developing clean technology manufactured goods for both internal and export markets.

If water scarcity issues are addressed, China could become a renewable hydrogen export champion, supplying international markets mainly in Southeast Asia. At a national level, our analysis clearly shows how renewable hydrogen could be most efficiently and effectively produced in the Southwestern region. A region where rich renewable resources

are available and water resources are less constrained, but far away from China's economic heartland, thus requiring significant infrastructure investments to connect supply with demand, potentially making regional imports more attractive.

From a geopolitical perspective, renewable hydrogen could become a key part of the Belt and Road Initiative, symbolizing China's technological prowess while increasing export opportunities and potentially enhancing Beijing's status as a leader in the global fight against climate change.

Making renewable hydrogen a significant part of China's future energy mix will require developing national and international policies and appropriate market structures aimed at spurring innovation along the value chains; scaling technologies while significantly reducing costs; and deploying enabling infrastructure.

Today, production from coal remains the lowest-cost option, about 30% cheaper than hydrogen from natural gas. Hence reducing the carbon footprint of coal-based hydrogen will be a critical factor in its viability in a low-carbon scenario, coal-based hydrogen with Carbon Capture Utilization and Storage (CCUS) is likely to remain the lowest-cost clean hydrogen production route for the middle-term.

China is piloting several new projects and policies, mainly in the mobility sector, but still has a long way to go before a hydrogen society reaches fruition. Yet if Beijing were to put its full manufacturing and policy might behind hydrogen's value chain, it would be a true game changer with cascading effects for the entire world.

1. Introduction

Hydrogen is gathering unprecedented momentum around the world. As governments become more serious about reducing emissions and addressing climate change, the spotlight has moved to the deep decarbonization of energy-intensive sectors. Especially those where electricity is not the preferred energy carrier and emissions are hard to abate, such as iron and steel production, high-temperature industrial heat, aviation, shipping, long distance road transportation and heat for buildings. Areas where the required dual transition — shifting to electricity as the preferred energy delivery system, while decarbonizing electricity production — may not work. Due to its versatility, hydrogen could play this role and serve as a “link” between emitting sectors.

Today, most of China’s hydrogen is produced from coal via 1,000 gasifiers, accounting for 5% of the country’s total coal consumption. While hydrogen burns cleanly at the point of use, in order to harness its full environmental benefit, it needs to be produced from zero-carbon electricity; otherwise the net result would only be to relocate emissions from one area to another.

Renewable hydrogen can be used for both stationary applications and mobility. As a readily-dispatchable means of storing energy, hydrogen technologies could help address power intermittency and curtailment¹ issues that will inevitably rise as renewable energy continues to alter China’s energy mix. China could use hydrogen to store utility-scale quantities of renewable resources. Hydrogen could also facilitate to store renewable energy at utility scale and serve as a fuel in stationary fuel cell systems for buildings, backup power, or distributed generation. As a sustainable mobility energy carrier, hydrogen could power fuel cell electric vehicles (FCEVs) and be the base for synthetic fuels. As a sustainable mobile energy carrier, hydrogen could power fuel cell electric vehicles (FCEVs) and form the base for synthetic fuels.

Hydrogen’s stationary applications have generally been more attractive than mobility applications; due to lack of enabling infrastructure and

¹ “Curtailment” refers to a situation in which a renewable energy plant is unable to operate at full capacity because of either oversupply or insufficient transmission capacity.

steadfast government support, but also to higher total ownership costs, and competition with electric vehicles (EVs). But in March 2019, the Chinese government took a step forward by announcing measures promoting the construction of hydrogen facilities for new energy vehicles (NEVs). Wan Gang, who is known as China's "father of electric cars", called for China to "look into establishing a hydrogen society" and "move further toward fuel cells."²

Given that Gang made a similar call two decades ago on vehicle electrification, which played a key role in China's current EV market dominance, close attention is warranted. If China were to replicate this success for hydrogen, it could be a game changer for the entire world, but innovation will be key to remove obstacles and accelerate adoption at scale.

The remainder of this paper is structured as follows: Section 2 outlines the measures introduced by the Chinese government to support the development of a hydrogen economy. Section 3 reviews hydrogen production pathways, costs, and market potential. Section 4 provides an overview of hydrogen fuel cell technology. Section 5 outlines the geopolitical and market map for renewably hydrogen in China. Section 6 analyzes the potential role of renewable hydrogen in China's transition to a low-carbon economy. Section 7 addresses policy and commercial options while section 8 provides an overall conclusion.

² Bloomberg (2019), "Wan Gang, China's father of electric cars, thinks hydrogen is the future" <https://www.bloomberg.com/news/articles/2019-06-12/china-s-father-of-electric-cars-thinks-hydrogen-is-the-future>, accessed April 7, 2020.

2. Government Support

In March 2019, the Chinese government announced some revisions to the annual Report on the Work of the Government³, which included measures promoting the construction of renewable hydrogen facilities for new energy vehicles (NEVs). During the summer, the Vice Chairman of China's policymaking board, Wan Gang, called for China to “look into establishing a hydrogen society” and “move further toward fuel cells.”

Is China putting its manufacturing and policy might behind hydrogen and fuel cells, just as it has with battery electric vehicles (BEVs)?

Over less than a decade, the Chinese government has used subsidies and other policies to forge the world's largest market for battery electric vehicles (BEVs). In 2018, 1.26 million EVs were sold in China, accounting for 60% of the world's total⁴. But in March 2019, to spur more competitive innovation in the sector, the government also announced that it would drastically reduce subsidies on NEVs by July 2019 and discontinue them by 2020.⁵ In July 2019, China's electric vehicle sales saw their first monthly decline of 4.7% from a year earlier, in August and September declines steepened, dropping by 16% and 34% to 85,000 and 80,000 units respectively⁶ (Figure 1).

³ National People's Congress of the People's Republic of China (2019). “Report on the Work of the Government” http://english.www.gov.cn/premier/speeches/2019/03/16/content_281476565265580.htm, accessed November 15, 2019.

⁴ Centre for Solar Energy and Hydrogen Research Baden-Württemberg (2020), <https://www.zsw-bw.de/en/media-center/data-service.html#c6700>, accessed April 3, 2020.

⁵ The Chinese government has been steadily reducing subsidies to progressively shift costs to its EV makers since 2016. The March 2019 measures saw government subsidies being totally removed for EVs with a range below 155 miles (250 km) while vehicles with higher ranges saw the incentives slashed by as much as 60%.

⁶ China Association of Automobile Manufacturers (2020), http://www.caam.org.cn/chn/21/cate_463/list_1.html, accessed April 3, 2020.

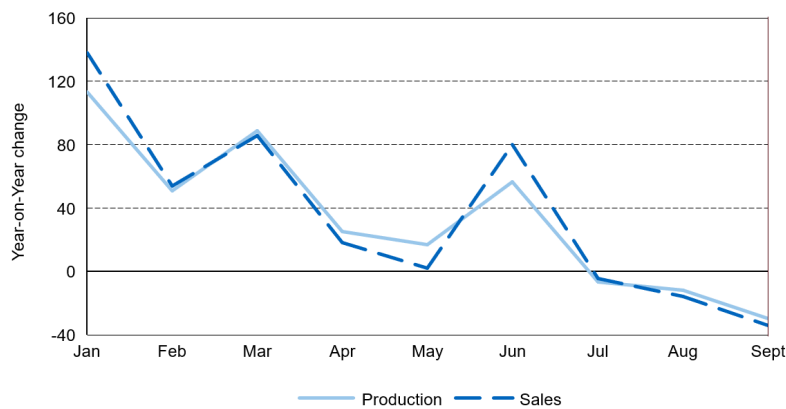


Figure 1. China's NEVs Production and Sales in 2019 (China Association of Automobile Manufacturers)

On the other hand, the month of June 2019 saw a jump in sales as consumers made purchases before possible price increases came into effect, as a result of the government's announcement. This even if EV makers will probably continue to prioritize volumes and market share over profitability, hence retail prices will likely remain at a similar level.

The Chinese government began introducing subsidies promoting vehicle electrification in 2010, driven largely by the need to reduce air pollution in the country's urban centers. This was only partly successful because the full environmental benefit of electrification can only be harnessed if electricity is produced from carbon-free sources and not from fossil fuel-based generation. In which case emissions simply transfer from vehicle combustion engines to coal plants, with insufficient or even negative impact on emissions.

China's new energy vehicle industry also benefitted from other policies aimed at shifting consumers away from internal combustion vehicles. For example, securing a license plate for new vehicles could take up to a year in many Chinese cities; while if purchasing an EV, license plates are issued along with the vehicle.⁷

⁷ MacDuffie, J. (2019), "China's Electric Vehicle Market: A Storm of Competition Is Coming" Wharton School of Management <https://knowledge.wharton.upenn.edu/article/chinas-ev-market/>, accessed March 4, 2020.

The Chinese government has also set aggressive goals for the deployment of FCEVs and the associated enabling infrastructure: hydrogen fueling stations. In 2017, China had approximately 1,200 FCEVs and less than 20 hydrogen fueling stations, ranking behind the United States, Japan, Germany and South Korea.⁸ The government now aims to have 5,000 FCEVs on the road by 2020; 50,000 by 2025; and one million by 2030. Guided by the target of one fueling station for every 1,000 vehicles, China plans to have 100 stations by 2020; 300 by 2025; and 1000 by 2030⁹ (see Figure 2). In comparison in the United States there are currently 41 fueling stations with 36 more being built, mainly in the state of California.^{10 11}

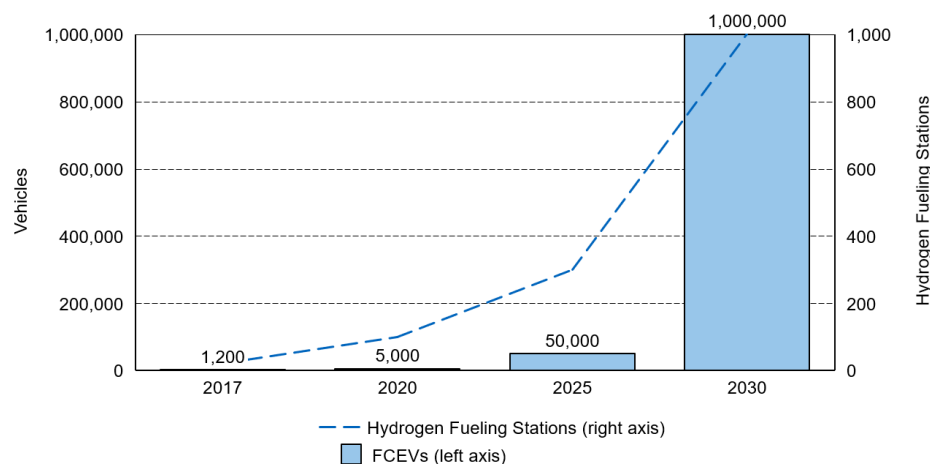


Figure 2. China's FCEVs and Infrastructure Development Plan (DOE 2018)

⁸ Hydrogen Fuel Cell Association (2020) "Transportation" <http://www.fchea.org/transportation>, accessed March 4, 2020.

⁹ U.S. Department of Energy (2020), "Hydrogen and Fuel Cells Update" https://www.energy.gov/sites/prod/files/2018/02/f49/fcto_h2_fc_update_satyapal_transp_research_board_2018.pdf, accessed March 4, 2020.

¹⁰ U.S. Department of Energy (2020), "Hydrogen Fueling Infrastructure Development" https://afdc.energy.gov/fuels/hydrogen_infrastructure.html, March 4, 2020.

¹¹ California Air Resources Board (2019), "2019 Annual Evaluation of Fuel Cell Electric Vehicle Deployment & Hydrogen Fuel Station Network Development"

In response to these government measures, Chinese automobile companies are making FCEVs a new focus for their business. Bloomberg NEF tracked more than \$17 billion worth of investments announced across the industry through 2023¹²; several examples are listed below. China National Heavy-Duty Truck Group's plans to invest \$7.6 billion to build FCEVs in Shandong province.

- Mingtian (Tomorrow's) Hydrogen, which is backed by the Chinese Academy of Sciences, plans to invest \$363 million in Anhui province to manufacture fuel-cell stacks and components. The company aims at a manufacturing capacity of 100,000 fuel-cell stacks by 2022 and 300,000 stacks by 2028.
- Great Wall Motor, one of the country's largest SUV and pickup manufacturers, has invested over \$149 million in research and development of hydrogen energy and FCEVs.¹³

¹² Bloomberg NEF (2019), "China's Hydrogen Vehicle Dream Chased With \$17 Billion of Funding" <https://www.bloomberg.com/news/articles/2019-06-27/china-s-hydrogen-vehicle-dream-chased-by-17-billion-of-funding>, accessed April 7, 2020.

¹³ China Daily (2019). "Great Wall Motor Bets Big on Hydrogen Fuel Cell Vehicles" <http://global.chinadaily.com.cn/a/201902/26/WS5c749b98a3106c65c34eb69d.html>, accessed April 3, 2020.

3. Production pathways, market potential and costs

Hydrogen is the most abundant element in the solar system, but on Earth, it naturally occurs only in its compound form. This means that hydrogen must be produced from molecules that contain it by means of specific processes: thermo-chemical conversion, biochemical conversion, or water electrolysis (see Figure 3).

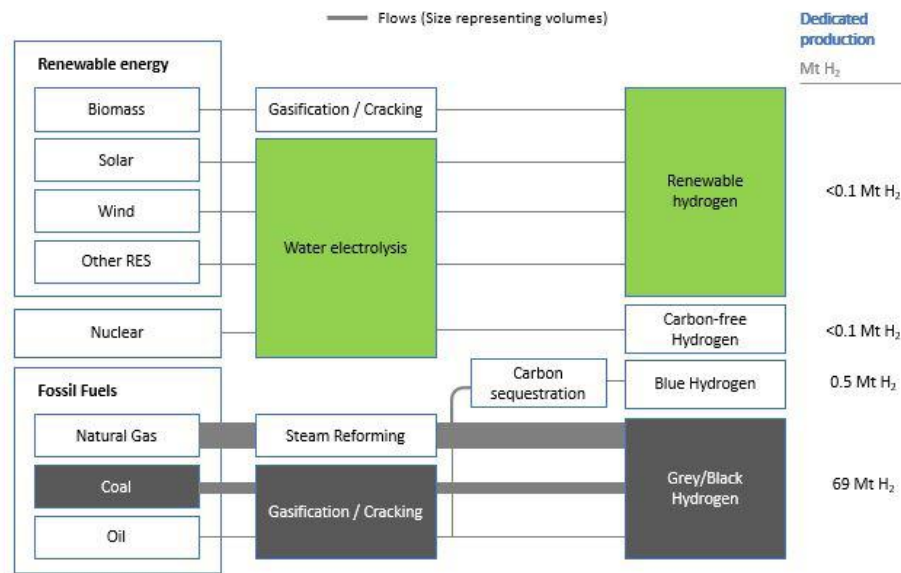


Figure 3. Hydrogen Production Pathways (IEA 2019 and authors' elaboration)

Global hydrogen production today, amounting to about 70 million tons (Mt) per year, is dominated by natural gas (steam reforming) and carbon (coal gasification) sources.¹⁴ China is by far the world's largest hydrogen producer: its 22 Mt per year represents roughly a third of the world's production. Most of China's hydrogen comes from coal, thanks to 1,000 coal gasifiers, accounting for 5% of the nation total coal consumption.^{15 16}

¹⁴ IEA (2019), "The Future of Hydrogen. Seizing today's opportunities. Report prepared by the IEA for the G20, Japan"

¹⁵ Brasington, L. (2019), "Hydrogen in China" Cleantech Group <https://www.cleantech.com/hydrogen-in-china/>, accessed April 1, 2020.

¹⁶ World Coal Association (2019), "Coal" <https://www.worldcoal.org/coal>, accessed March 4, 2020.

To reap renewable hydrogen's full environmental benefits, hydrogen must be produced from zero carbon sources like renewables and/or nuclear energy. While hydrogen burns cleanly as fuel at its point of use, if produced from fossil fuels the net result would only be to relocate emissions from one area of the country to another.

Our research focuses on the production of renewable hydrogen through water electrolysis, an electrochemical process that splits water into hydrogen and oxygen. Electrolysis currently accounts for less than 3% of global hydrogen production (and less than 1% of dedicated production). Yet there are significant opportunities for growth, especially in China, if surplus electricity from renewables and/or nuclear becomes more available and production costs decrease.

3.1 Market potential

Today, renewable hydrogen is mainly used in oil refining and the production of ammonia/fertilizers, methanol, and/or steel production. In China, hydrogen's traditional use as a feedstock stems from the country's dominance in ammonia markets, holding about a 30% share of global production.¹⁷

Estimates on annual hydrogen demand by 2050 vary significantly among scenario analyses. The 2017 Hydrogen Council study estimates global demand at approximately 78 EJ, or around 14% of the expected world's total energy demand. Studies by BNEF (2019) and DNV GL (2018) are more conservative, with estimates between 5 and 39 EJ. And Shell (2018) predicts no considerable growth by 2050. Figure 4 provides a comparison of these estimates.

¹⁷ U.S. Geological Survey (2020), "Nitrogen - Mineral Commodity Summaries, January 2020".

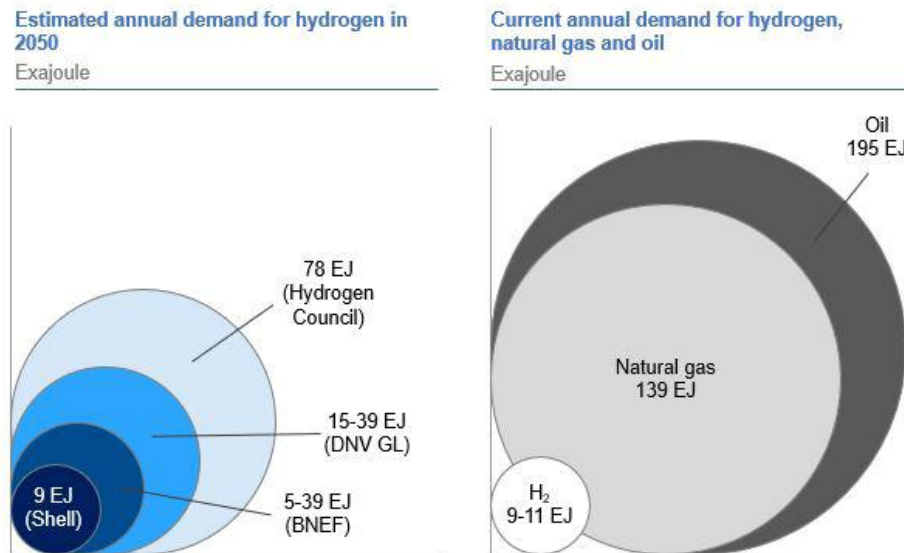


Figure 4. Hydrogen market in 2050. (Hydrogen Council 2017, BNEF 2019, DNV GL 2018, Shell 2018, IEA 2019, BP 2019)

3.2 Production costs

Hydrogen costs vary significantly as a function of production technology and prices for fossil fuels, electricity, and carbon. In China, production from coal remains the lowest cost option: about 30% cheaper than hydrogen from natural gas. Therefore, reducing the carbon footprint of coal-based hydrogen will be critical in a low-carbon economy. In the medium term, coal-based hydrogen with carbon capture, utilization and storage (CCUS) will likely remain China's lowest-cost clean hydrogen production pathway¹⁸ (see Figure 5).

For domestic renewable hydrogen production to become competitive, China must work towards lower electrolysis costs and greater electrolysis efficiency, as well as lower prices for renewable electricity. While technology innovation and economies of mass production are expected to drive down electrolysis costs, using excess renewable electricity could further lower costs considerably. Producers could also focus on exports markets in places like Japan, which could yield better profits.

¹⁸ CAPEX of coal with CCUS = USD 1 475/kWh₂.

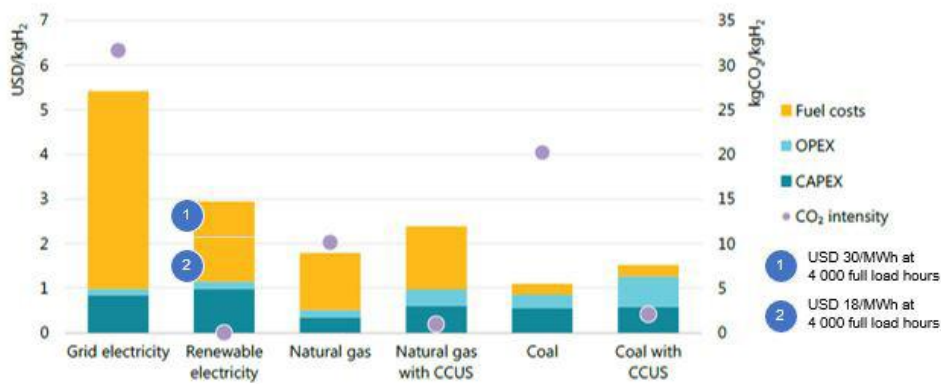


Figure 5. Hydrogen production costs in China (IEA 2019; authors' calculations)

3.3 CO₂ Intensity

China's dependence on coal-based hydrogen yields high levels of carbon emissions: ca. 20 tons of carbon dioxide per ton of hydrogen (tCO₂/tH₂). A shift to natural gas-based hydrogen would reduce emissions by half (ca. 10 tCO₂/tH₂).¹⁹ Due to China's extensive coal mining infrastructure and lack of domestic natural gas, it is unlikely the country will be able to eliminate coal-based hydrogen in the medium term. Though coal plants utilizing CCUS are well-suited to mitigating emissions, only the adoption of renewable hydrogen at scale, with its zero carbon impact, would fully address these concerns.

¹⁹ IEA (2019), "The Future of Hydrogen. Seizing today's opportunities. Report prepared by the IEA for the G20, Japan".

Nuclear hydrogen: an enabler in China's transition to a low-carbon economy?

The Chinese government sees nuclear power as a clean energy source that would help meet its long-term climate and air pollution goals without hampering economic growth. For this reason, China is currently building or planning more than fifty new nuclear reactors,²⁰ an ambitious endeavor that stands in stark contrast to global trends.

At the same time, nuclear power faces some significant economic challenges: not only the associated construction costs, but also the impact of subsidized intermittent renewables, curtailment issues, and low-cost natural gas generation competition. Hence, utilities are economically incentivized to consider integrating nuclear energy with other industrial processes to optimize thermal and electrical energy production.

Low-cost, carbon-free hydrogen offers a promising solution and would provide much needed additional revenue streams for nuclear power plants. Depending on local conditions, various approaches could be considered: using electricity to produce hydrogen through water electrolysis; using electricity and heat to produce hydrogen through extremely efficient high-temperature electrolysis; or (though not zero-carbon) using steam in natural gas-based steam methane reforming to reduce hydrogen's production costs and carbon intensity.

²⁰ World Nuclear Association (2020), "Nuclear Power in China" <https://www.world-nuclear.org/information-library/country-profiles/countries-a-f/china-nuclear-power.aspx>, accessed April 7, 2020.

4. Technology focus: hydrogen fuel cells

Hydrogen can be used both in mobility and in stationary applications; as a mobility energy carrier, it can power fuel-cell electric vehicles (FCEVs) and/or be a feedstock for synthetic fuels. In stationary applications it can be used as a means for storing renewable energy at utility scale but also off grid. Hence providing backup power to buffer RES intermittency and/or serve as a carbon-free heating source.

What is a fuel cell?

Fuel cells convert hydrogen-rich fuels into electricity through a chemical reaction. If hydrogen is the fuel, electricity, water, and heat are the only end products.

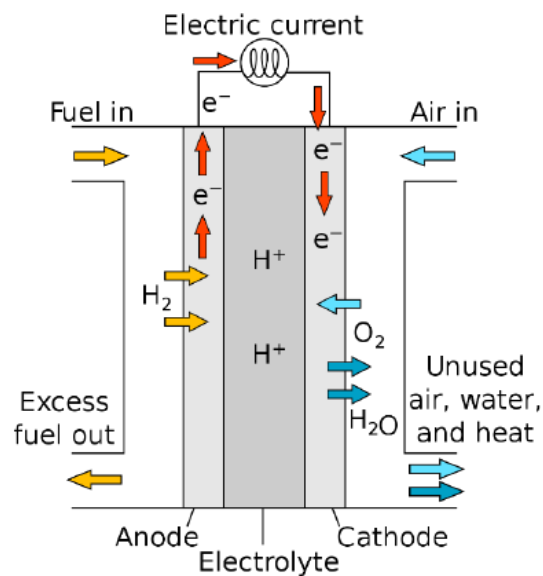
Fuel cells do not need to be periodically recharged like batteries, and since they have no moving parts, they operate near-silently.

Fuel cells possess a unique wide variety of potential applications; they can power systems as large as a utility power station or as small as a laptop computer or function as internal combustion engine replacements for electric vehicles.

How does a fuel cell function?

- A fuel cell is composed of an anode, a cathode, and an electrolyte membrane.
- At the anode, hydrogen is split into protons and electrons.
- Protons pass through the electrolyte membrane, while the electrons are forced through a circuit, generating an electric current and excess heat.
- At the cathode, protons, electrons, and oxygen combine to produce water molecules.

Source: Irados (Wikimedia Commons)



4.1 Fuel Cell Electric Vehicles (FCEVs) and Renewable Hydrogen

Fuel cell vehicles are electric vehicles which use a fuel cell, instead of a battery to power electric motors. Hydrogen fuel cell electric vehicles offer a unique combination of features as a zero-emission alternative not only to conventional vehicles, but also to BEVs which use lithium ion batteries to store electrical energy produced outside the car.

Hydrogen FCEVs produce no tailpipe emissions: simply water vapor and warm air. While clean burning by themselves, the full environmental benefit can only be harnessed if hydrogen is produced from renewable or nuclear energy.

Driving ranges vary for FCEVs but are very similar to those of conventional vehicles (400-600 km).²¹ Customers are expected to have similar experiences at hydrogen refueling stations as at gasoline stations, with most hydrogen dispensers being added at existing gasoline stations.

The refueling experience is comparable to refueling a conventional car, taking less than five minutes²² to fill current models (Figure 6), while charging a BEV can take as little as 20 minutes or as much as 12 hours depending on the size of the battery and the speed of the charging point.²³ Currently pressurized hydrogen is sold at either 350 bar (35 MPa) or 700 bar (70 MPa).

²¹ Kurtz, J., et al. (2019), "Fuel Cell Electric Vehicle Driving and Fueling Behavior" National Renewable Energy Laboratory <https://www.nrel.gov/docs/fy19osti/73010.pdf>, accessed March 4, 2020.

²² U.S. Department of Energy (2020), "Alternative Fuels Data Center – Hydrogen Basics" https://afdc.energy.gov/fuels/hydrogen_basics.html, accessed March 4, 2020.

²³ U.S. Department of Energy (2020), "Vehicle Charging" <https://www.energy.gov/eere/electricvehicles/vehicle-charging>, accessed May 12, 2020.

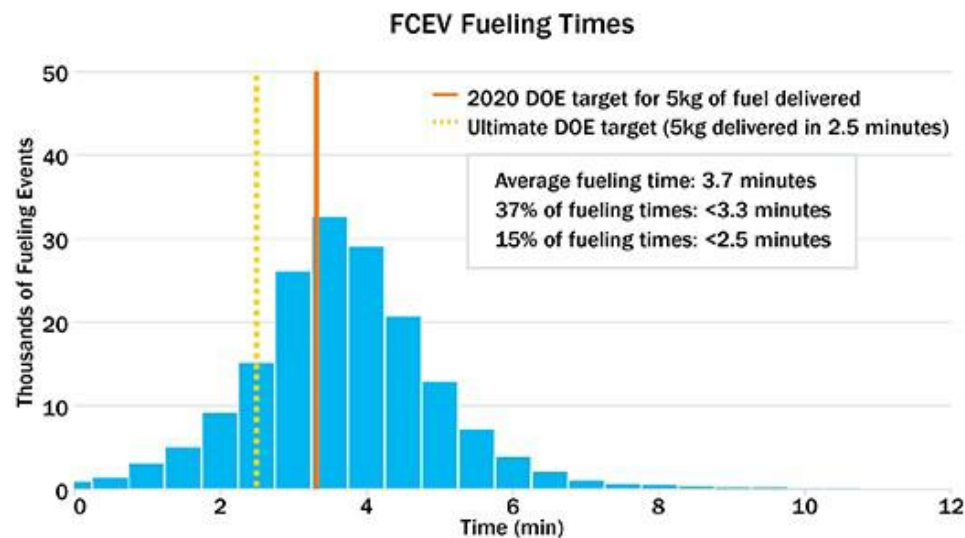


Figure 6. U.S. targets for FCEV fueling times (U.S. Department of Energy)

4.2 Outlook

The adoption of hydrogen vehicles is not as easy as it might seem; otherwise FCEVs would already dominate battery-powered cars and internal combustion engines around the world. There are significant issues hindering their deployment at scale. First, fuel cells are more expensive than batteries, and hence less competitive due to the higher total cost of car ownership. Second, as discussed, there is a significant lack of enabling infrastructure, from pipelines to fueling stations.

Building a hydrogen fueling station currently costs between \$1 and 2 million (around \$1.5 million in China).²⁴ This compares to an estimated \$200,000 for an ultra-fast-charging electric-vehicle station equipped with a single 350-kW charger.²⁵ Obviously a tough investment to make, especially when there are so few vehicles operating; and yet lack of refueling is usually cited as the biggest obstacle to widespread adoption of FCEVs

²⁴ The International Council on Clean Transportation (2017), "Developing hydrogen fueling infrastructure for fuel cell vehicles: A status update".

²⁵ Franc, P. (2019), "Costs Check Growth of Fuel-Cell Infrastructure" <https://www.wardsauto.com/technology/costs-check-growth-fuel-cell-infrastructure>, accessed April 6, 2020.

Most likely, the widespread adoption of hydrogen will only be feasible if governments facilitate and subsidize the deployment of enabling infrastructure while supporting further R&D efforts to drive down equipment costs. Governments may be interested in doing so for multiple environmental, economic, and geopolitical reasons as described in the next sections.

Toyota Mirai “Future”

- 151 horsepower, 9 second 0-100 km/h
- Range is around 500 km
- Hydrogen fuel cell located under the front seats
- Battery in the trunk to store energy
- Refueling takes about five minutes
- Cost of fuel included for first three years of ownership
- Vehicle price: \$70,000 USD (unsubsidized)

Source: Toyota (2019)



5. The geopolitical and market map for renewable hydrogen

Our recent research explored the global implications of renewable hydrogen adoption and showed that the role countries will likely assume in global renewable hydrogen markets depends on their renewable energy resource and freshwater endowments as well as their ability to deploy enabling infrastructure at scale – referred to as infrastructure potential.²⁶ We have applied this analytical framework to focus on China and the role hydrogen could play in its transition to a low-carbon economy.

5.1 Renewable energy resources (RES) endowment

A country's RES endowment is defined as the combined generation potential of wind and solar power.²⁷ As a key variable in the production of renewable hydrogen, RES endowment affects production capacity that a region could attain.

We consider a country's RES endowment poor if its potential for renewable generation is less than 1.5 times its domestic primary energy consumption across all sectors.²⁸ Space constraints may also emerge for countries with high population density (above 150 inhabitants per square kilometer). In these denser nations, finding land for RES infrastructure forces competition with other industries such as agriculture and transportation. Neither of these constraints apply to China.

We consider a country's RES endowment abundant if renewable generation potential exceeds domestic primary energy consumption by about 5% of current global primary energy consumption (equivalent to 7.5 PWh). China has a RES potential of about 98.2 PWh, compared to its 34.8 PWh primary energy consumption. Therefore, the country could export up to

²⁶ Pflugmann, F., and De Blasio, N. (2020). "The Geopolitics of Renewable Hydrogen in Low-Carbon Energy Markets," *Geopolitics, History, and International Relations* 12(1): 9–44. doi:10.22381/GHIR1210201.

²⁷ The combined renewable generation potential is calculated based on the wind power potential of a country derived from NREL (2014) and solar power potential derived from Pietzcker et al. (2014).

²⁸ Primary energy consumption was derived for the year 2013 from EIA (2019).

63.4 PWh of excess renewable energy after meeting its internal energy demand.²⁹

A country's RES endowment also indicates attainable cost ranges for renewable electricity generation: higher resource endowment often translates into higher capacity, which in turn influences generation costs.

Figures 7 and 8 depict the spatial distribution of China's solar irradiation and wind speed potential, as well as the high RES potential of China's southwestern and northern regions.

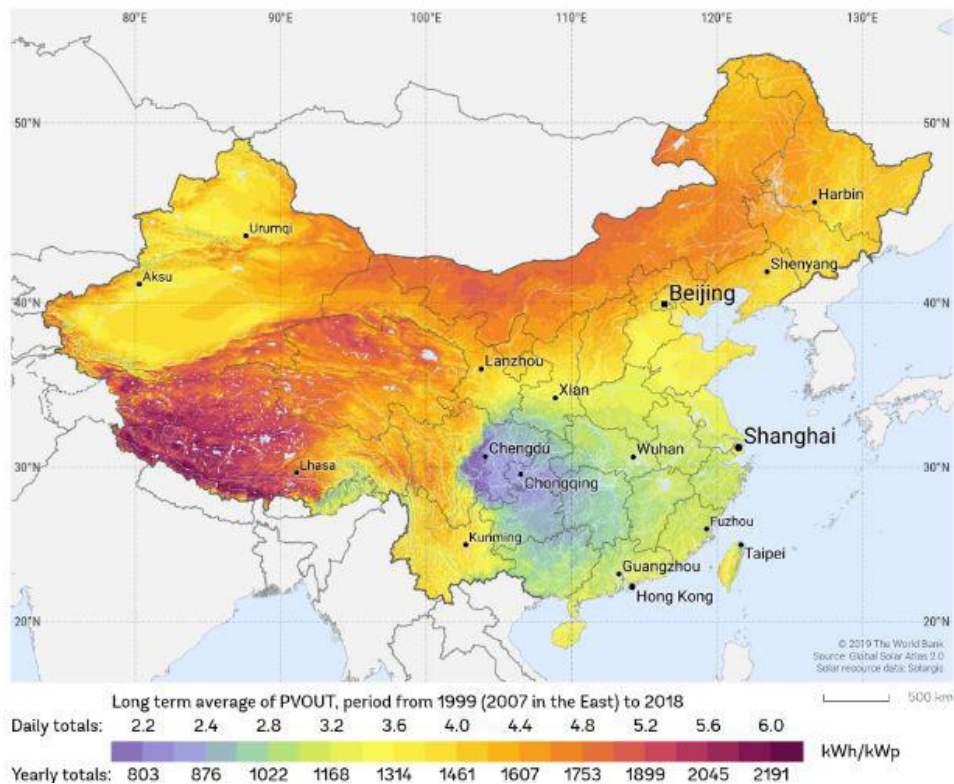


Figure 7. China's annual photovoltaic potential (Global Solar Atlas 2019)

²⁹ We assume that among all renewable energy sources, solar and wind power will become dominant sources due to their large-scale potential and favorable cost structures and hence primarily used in renewable hydrogen production in our scenario, even if also hydropower and/or nuclear could contribute. Today hydropower plays an important role in Chinese clean energy mix with a generation capacity of 1.2 PWh (hydro plus pumped storage, see International Hydropower Association) but regardless shows a limited growth potential compared to solar and wind.

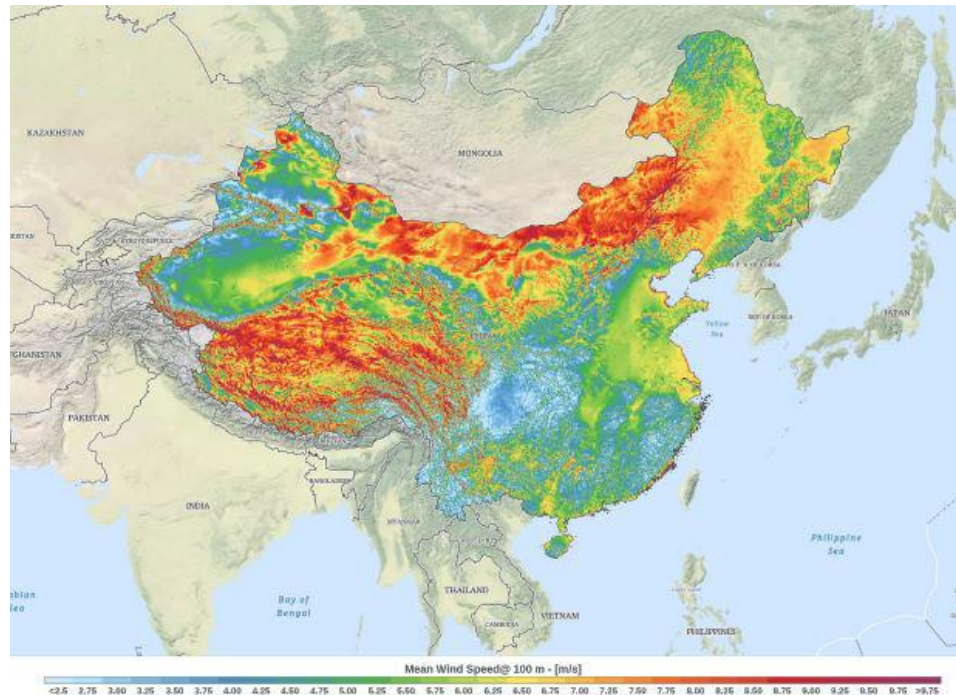


Figure 8. China's mean annual wind speed (Global Wind Atlas 2019)

5.2 Renewable freshwater resources endowment

Besides renewable electricity, freshwater is the other key variable for renewable hydrogen production. Therefore, the availability of freshwater resources has a direct impact on the renewable hydrogen generation capacity potential of a region.

A country's freshwater resources supply is considered scarce if its total annual internal renewable freshwater resources are under 800 m³ per inhabitant.³⁰ Water resources in these countries are used predominantly for drinking, household consumption, industrial use, and irrigation. Our data for global renewable freshwater resources is derived from AQUASTAT³¹.

³⁰ For comparison: the United States withdraws 1,369 m³ per inhabitant, India 602 m³ per inhabitant and Germany 309 m³ per inhabitant. Countries with limited freshwater resources tend to withdraw proportionately more in order to irrigate their fields.

³¹ AQUASTAT is a global water information system developed by the Food and Agriculture Organization of the United Nations. See FAO (2016),

While China is not considered water-constrained as a whole, freshwater availability varies greatly among regions³² (Figure 9). Water scarcity is already a serious issue, especially impacting the urban centers and industrial zones of the North. Furthermore, increasing industrialization poses growing threats to the nation's access to adequate freshwater resources. Eleven Chinese provinces are already water-constrained: Beijing, Gansu, Hebei, Henan, Jiangsu, Liaoning, Ningxia, Shandong, Shanghai, Shanxi, and Tianjin. And seven more are at risk of becoming water-constrained: Anhui, Chongqing, Guangdong, Hubei, Inner Mongolia, Jilin, and Shaanxi.

By overlapping these first two variables, we can draw a key insight on the challenges associated with the development of China's domestic renewable hydrogen industry. The comparison clearly shows how renewable hydrogen could be most efficiently and effectively produced in the Southwestern region. Where, rich renewable resources are available and water resources are less constrained, yet far away from China's economic heartland, requiring significant infrastructure investments to connect supply with demand, potentially making imports more attractive.

The latter point would also be true if other forms of water consumption were to be prioritized over renewable hydrogen production. This would require Beijing to evaluate how to best meet domestic renewable hydrogen needs and possibly initiate trade partnerships and devise strategies to secure diversified hydrogen supplies.

³² China Water Risk Project (2017), "Who is running dry?" <http://www.chinawaterrisk.org/the-big-picture/whos-running-dry/>, accessed December 18, 2019.

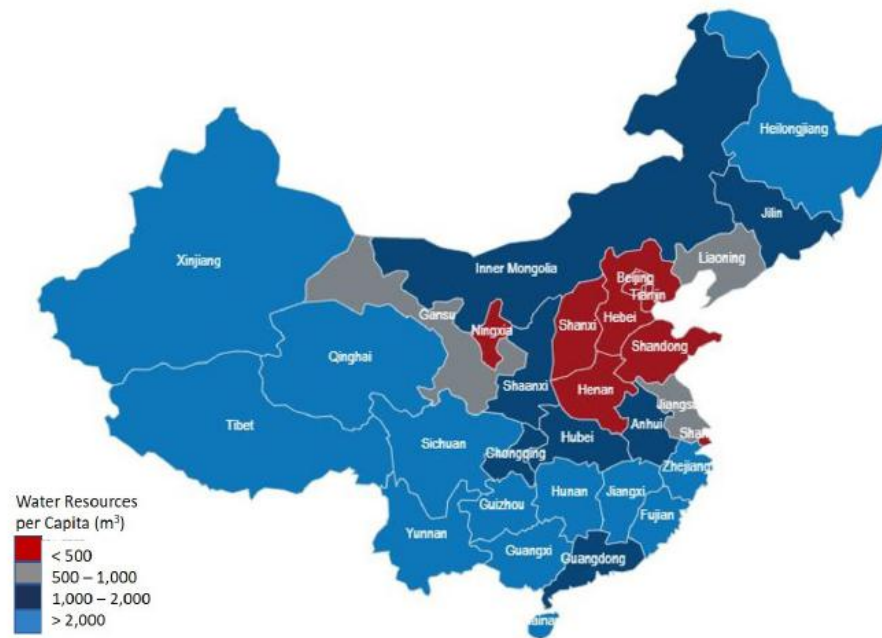


Figure 9. Water resources per capita (China Water Risk Project 2017)

5.3 Infrastructure potential

Countries with the technical and financial resources to design, build and operate the needed infrastructure systems will have a key competitive advantage in emerging hydrogen economies. As of today, no country possesses considerable renewable hydrogen production facilities or widespread transportation infrastructure. Therefore, we must rely on the strength of existing infrastructure to estimate a country's ability to build and operate hydrogen production, transportation and distribution infrastructure.

Our proxy measurement is the overall infrastructure score in the World Economic Forum's 2019 Global Competitiveness Index. Countries with scores below 4 on a 1-7 scale are considered infrastructure constrained. For our analysis, China (with a score of 4.5) is not considered infrastructured constrained³³.

The following table aggregates countries into 5 groups based on these three parameters. For a detailed global map of renewable hydrogen markets and geopolitics, see Figure 10. Our analysis considers China as renewable-rich, yet partly water-constrained, with high infrastructure potential, and the capacity of becoming an "export champion" if water scarcity issues are addressed. On the other hand if these issues were to persist, it might prove more affordable for some Chinese regions to forgo extensive infrastructure development and import hydrogen from neighboring countries instead.

³³ It should be noted that the evaluation of a country's infrastructure potential also includes considerations on financial variables (e.g. access to capital markets, credit rating, cost of capital) and political stability. The lack of these enabling factors would significantly hamper a country's ability to develop infrastructure even today; hence, these are indirectly accounted for in the evaluation of a country's infrastructure potential.

#	Group	Resource endowment		Infrastructure potential	Example countries
		Renewable energy resources	Renewable freshwater resources		
1	Export champions with vast renewable energy and water resources, as well as high infrastructure potential	++	+	+	Australia, United States, Morocco, Norway
2	Renewable-rich, but water-constrained nations with high infrastructure potential	++	--	+	Saudi Arabia, potentially China
3	Renewable-constrained nations with high infrastructure potential	-	+	+	Parts of the EU, Japan, Korea
4	Resource-rich nations with high infrastructure potential	+	+	+	Turkey, Spain, Thailand
5	Resource-rich countries with low infrastructure potential	+	+/-	-	Most parts of South America

Legend: Abundant/very high (++); Available/high (+);
 Poorly available/constrained (-); Scarce/highly constrained (--)

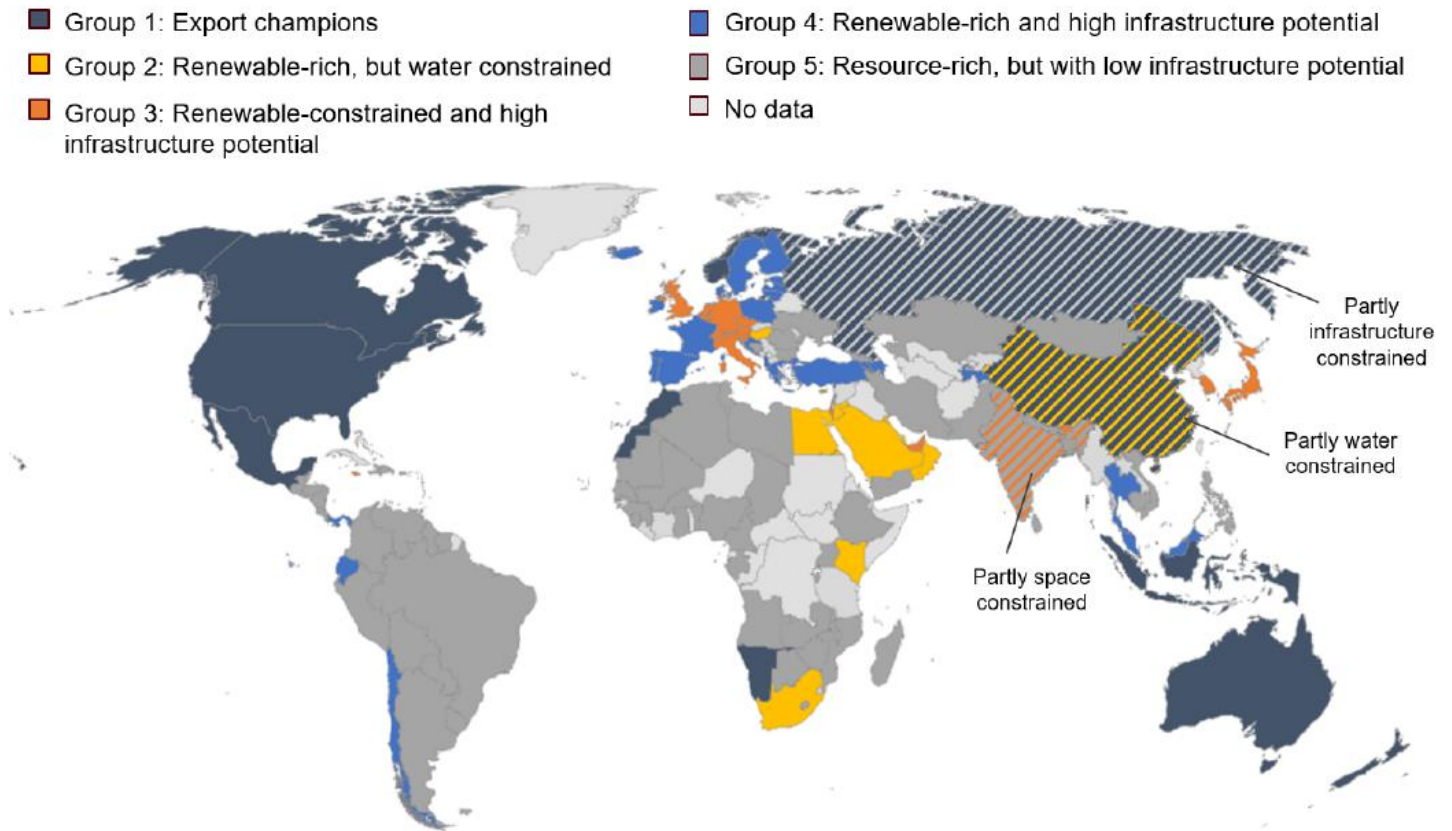


Figure 10. The global renewable hydrogen map. (Authors' illustration)

6. Potential role of renewable hydrogen in China's transition to a low carbon economy

Renewable hydrogen can help accelerate China's transition to a low-carbon economy, while significantly reducing fossil fuel dependence and opening new avenues for economic growth. In the following section we summarize some of the significant overall advantages that embracing hydrogen could offer China.

As a clean energy carrier, renewable hydrogen can contribute to China's political imperative of reducing air pollution levels, especially in the eastern economic heartland. At the same time, developing China's renewable hydrogen value chain would complement climate mitigation measures Beijing has already taken in order to meet its Paris Agreement target of reaching a CO₂ emission peak by 2030.³⁴

Alternative energy carriers, like renewable hydrogen, will also be key to decarbonizing hard to abate sectors such as iron and steel production, high-temperature industrial heat, and heat for buildings. Sectors in which the necessary dual transition (shifting to electricity, as the preferred energy delivery system, while decarbonizing electricity production) may not work. As a sustainable mobility energy carrier, hydrogen could power fuel cell electric vehicles and/or form the base for synthetic fuels³⁵, thus tackling other hard to abate sectors like aviation, shipping, and long-distance road transportation.

Hydrogen could also contribute to China's goal of increased energy independence. While fossil fuels have driven the tremendous economic growth of the past, China's future energy strategy will likely aim to break ties between economic growth and the use of fossil fuels, as domestic natural resources are depleting. For example, China has recently tried to curb its energy dependence by limiting coal imports from Australia. Domestically

³⁴ Gallagher, K.S., et al. (2019), "Assessing the Policy gaps for achieving China's climate targets in the Paris Agreement" Nat Commun 10, 1256. <https://doi.org/10.1038/s41467-019-09159-0>.

³⁵ Hydrogen can be combined with carbon dioxide to form synthetic hydrocarbons or synthetic liquid fuels which can be used as drop in fuels in existing infrastructure. The needed carbon dioxide could be supplied from carbon-emitting power plants or industrial facilities; alternatively, it could be captured directly from the atmosphere.

produced hydrogen could serve both agendas: reducing pollution and emissions while limiting dependence on foreign energy imports.

Second, the reality that China is the world's largest consumer of coal should not distract from the fact that it is also the world's largest developer of renewable energy. As a readily dispatchable means of storing energy, hydrogen can help to address intermittency and curtailment issues³⁶ as renewable energy increases its share in the Chinese energy mix. Due to the geographical generation split in the northwest and load consumption in the eastern coastal provinces, wind and solar curtailments have been a chronic policy challenge in China in recent years, indicating an urgent need for additional power sector reform. Coupling decentralized hydrogen generation with not yet connected or poorly connected decentralized renewable generation would allow to produce renewable hydrogen with this excess electricity, thus becoming a reliable low-cost hydrogen source.^{37 38}

Third, hydrogen can also open new avenues for developing clean technology manufactured goods³⁹ for both internal and export markets. Following China's economic transformation from agrarian economy to a global industrial powerhouse, the country seeks new avenues for further economic growth and employment opportunities. Certainly, China will strive to develop an even more complex economy, likely expanding the service sector and cultivating up-and-coming sectors such as cleantech. Indeed, China has already created more jobs in the renewable energy sector than any other country in the world by far.⁴⁰

As in the solar photovoltaics industry, where Chinese manufacturers dominate European and American producers in scale and cost-competitiveness, China could establish itself as the world's leading technological and economic hub for hydrogen. Associated economic gains would be significant:

³⁶ "Curtailment" refers to a situation in which a renewable energy plant is unable to operate at full capacity because of either oversupply or insufficient transmission capacity.

³⁷ Huenteler, J., et al. (2018), "Why is China's wind power generation not living up to its potential?" *Environ. Res. Lett.* 13 044001.

³⁸ Standaert, M. (2019), "Why China's Renewable Energy Transition Is Losing Momentum" *Yale Environment* 360.

³⁹ Clean technology manufacturing aims at minimizing the energy and environmental impacts of the production, use, and disposal of goods, ranging from commodities such as metals and chemicals to final-use products such as airplanes and wind turbine blades, through the use of clean energy and the development of new materials and process technologies.

⁴⁰ McCarthy, N. (2019), "The State of Global Renewable Energy Employment" *Forbes*. <https://www.forbes.com/sites/niallmccarthy/2019/07/23/the-state-of-global-renewable-energy-employment-infographic/#669213e6e63f>, accessed April 6, 2020.

according to the Hydrogen Council, hydrogen markets and technologies could generate more than \$2.5 trillion per year and provide employment for 30 million people around the world.⁴¹

Fourth, if water scarcity issues are addressed, China could become a hydrogen “export champion.” While China has abundant renewable energy resources, freshwater resources vary significantly among regions, challenging China’s likelihood of emerging as an international supplier. Furthermore, increasing industrialization will pose growing threats to the nation’s access to adequate freshwater resources, further stressing China’s water infrastructure. Hence, China could be forced to import renewable hydrogen, even if it could theoretically meet its domestic demand without turning to foreign markets. Alternatively, hydrogen production could be focused in China’s Southwest, where rich renewable resources are available and water resources are less constrained. However, extensive pipelines (around 2,500 km) would need to be built to funnel hydrogen to demand centers in the East. Our analysis shows that in the long term, domestic renewable hydrogen production and transportation (by pipeline) could become competitive at around 3-4 USD/kgH₂; imports from Australia would cost around 4-5 USD/kgH₂ based on ammonia shipping and re-conversion to hydrogen.⁴²

Nevertheless, water constraints might make it more feasible to forgo extensive infrastructure development and import hydrogen from neighboring countries instead. While resource-rich regions in the southwestern China could consider exporting renewable hydrogen to neighboring countries, like India. India, due to its infrastructure challenges throughout the vast subcontinent the country spans, will likely employ a mix of off-grid and large-scale grid solutions to produce renewable hydrogen. But to support its extremely dense populations, especially in the region neighboring China, India may also need to import large quantities of hydrogen.

To address water scarcity in certain regions, China could also consider using seawater instead of freshwater for renewable hydrogen production. However, this approach would require desalination ahead of electrolysis,

41 Hydrogen Council (2017). “Hydrogen – Scaling up. A sustainable pathway for the global energy transition.”

42 IEA (2019), “The Future of Hydrogen. Seizing today’s opportunities. Report prepared by the IEA for the G20, Japan”, and authors’ calculations.

increasing production costs (about 0.5 to 2.0 USD/m³ for large-scale desalination plants⁴³). Scientific breakthroughs allowing direct seawater electrolysis could significantly improve China's likelihood of leading the world as a hydrogen supplier.⁴⁴

43 Brian et al. (2008), "Estimating the cost of desalination plants using a cost database" *Desalination* 229 (1-3): 10-20 doi.org/10.1016/j.desal.2007.07.023.

44 Kuang et al. (2019), "Solar-driven, highly sustained splitting of seawater into hydrogen and oxygen fuels" *PNAS* 116(14): 6624-6629.

7. Policy and commercial options

Policy makers and investors must cultivate a thorough understanding of the nascent dynamics of renewable hydrogen and its potential impact on global markets. This in order to better navigate the challenges and opportunities of a low-carbon economy without falling into the traps and inefficiencies of the past.

Stakeholders need to first assess the economic, environmental, and geopolitical implications of renewable hydrogen; then, they need to develop proactive strategies to address these implications and define plans for implementation. Corporations and investors need to develop business models that offer prospects of acceptable returns, while government policies need to be imaginative and supportive by design, keeping in mind that the market dynamics of renewable hydrogen are comparable to natural gas and not renewables (e.g., wind and solar power).

First and foremost, China must decide on the role it will play in future renewable hydrogen markets: will Beijing establish itself as a renewable hydrogen export champion? To assume a dominant role as hydrogen markets emerge, China must define new policies to effectively trigger investments in renewable hydrogen production and the at scale deployment of enabling infrastructure. Furthermore, since China is partially water-constrained, the government will also need to determine the resources it needs to allocate for renewable hydrogen production, considering the direct competition with other water-intense sectors, such as agriculture.

Increasing renewable hydrogen production will require sustained development of renewable generation capacity, driving commercialization of electrolysis technology, deploying enabling infrastructure and as discussed, addressing water scarcity issues, including investments into desalination plants to remove water supply bottlenecks.

Targeted policies paired with direct government support will help China lower market risks while addressing commercialization barriers. Since the renewable hydrogen industry is still nascent from a research and development point of view, China should further focus on funding innovation and/or regional projects. A targeted innovation agenda aimed at removing key bottlenecks would deliver major returns for China. These policies would contribute to achieve the required economies of scale, and eventually reach the tipping point at which renewable hydrogen technologies become cost competitive.

In parallel, we believe policies focused on reducing market risk are key to secure the private investments needed for commercialization at scale. China should also initiate cooperation with potential importing countries, such as Japan or South Korea, to facilitate longterm contracts and foreign investments to further reduce market risk and beginning to establish international standards for renewable hydrogen production, certification, transportation, and use.

Internally, China's government should revisit its own regulatory frameworks to ensure that oversight is streamlined for new regulations and any safety issues are resolved.

To incentivize investments China should also introduce measures to stimulate local renewable hydrogen markets. Examples include defining blend-in quotas for natural gas grids and/or setting renewable hydrogen standards requiring that defined percentages of total hydrogen production come from renewable resources. Moreover, China should consider the emergence of new markets for ammonia as an energy carrier due to its higher energy density.

As previously discussed, policies should continue to support the use of hydrogen as a sustainable mobility energy carrier, and this will require defining the role hydrogen should play in China's transportation sector. Key questions to shape these policies include: how should a reliable supply chain for renewable hydrogen be configured (ranging from hydrogen production to refilling stations)? How and where should enabling infrastructure be deployed? What is the timeline for the ramp-up? Which

applications should fuel cell vehicles address compared to other technologies, such as EVs and internal combustion engines? For the latter question, once infrastructure issues are addressed, we believe that FCEVs and BEVs will more likely complement each other rather than compete. This because while BEVs are well-suited for every day, short distance trips such as commuting, FCEVs boast clear advantages for large and heavy duty vehicles as well as vehicles with high up-time, such as public buses and commercial vehicles.

Finally, from a geopolitical point of view, as it is the case for nuclear power, renewable hydrogen could become a key part of the Belt and Road Initiative (BRI), Beijing's signature regional and global vision aimed at expanding China's geopolitical goals through numerous infrastructure projects.⁴⁵ Renewable hydrogen could become a symbol of China's technological prowess and export opportunities, while potentially enhancing Beijing's international status as a leading nation in the global campaign to fight climate change.

⁴⁵ The State Council of the People's Republic of China (2020), "The Belt and Road Initiative" <http://english.www.gov.cn/beltAndRoad/>, accessed April 1, 2020.

8. Conclusion

Hydrogen is gaining unprecedented momentum around the world. In China, renewable hydrogen could be used for both stationary and mobility applications. As a sustainable mobility energy carrier, it can power fuel-cell electric vehicles and/or be the base for synthetic fuels. In stationary applications it can be used to store renewable energy—both at utility scale and/or off-grid—hence providing backup to buffer renewable energy sources (RES) intermittency and/or serve as a carbon-free heating source.

Using the same analytical framework outlined in our companion paper, “The Geopolitics of Renewable Hydrogen in Low-Carbon Energy Markets,” we examined the potential and implication of wide-spread use of renewable hydrogen in China. While China has access to vast renewable energy resources and the potential to build hydrogen production and transportation infrastructure at scale, water scarcity in the eastern part of the country might limit its ability to develop the country’s renewable hydrogen industry. However, these issues could be addressed by investing in desalination plants and/or developing cross-national transportation infrastructure to bring hydrogen from the water and renewable-rich western areas to eastern industrial and urban centers.

For the Chinese government, hydrogen – if produced with renewable energy – could be key in the transition to a low-carbon economy. A full-fledged renewable hydrogen industry would:

- Offer a way towards meeting climate and pollution goals.
- Avoid increased reliance on imported fuels.
- Address renewable energy intermittency and curtailment issues.
- Open new avenues for developing clean technology manufactured goods.

Furthermore, if China prioritizes its water scarcity issues, the country is poised to emerge as a hydrogen export champion, supplying international markets in Southeast Asia and beyond. From a geopolitical point of view, renewable hydrogen could become a key part of the Belt and

Road Initiative and a symbol of China's technological prowess and export opportunities.

For renewable hydrogen to become a significant part of China's low-carbon energy mix, Beijing will need to define new and innovative national and international policies while developing appropriate market structures aimed at spurring innovation along the value chains; scaling technologies while significantly reducing costs; and deploying enabling infrastructure at scale.

China still has a long way to go before a hydrogen society reaches fruition, but if the nation were to put its manufacturing and policy might behind hydrogen, this would be a true game changer with cascading effects for the entire world.

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